UPDATED BIOFIDELITY RATING OF THE REVISED WORLDSID PROTOTYPE DUMMY

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ABSTRACT

Aiming to obtain a new, advanced, globally harmonised mid-sized male side impact dummy the WorldSID (**World**wide **S**ide **I**mpact **D**ummy) has been developed under the auspices of the International Organisation for Standardisation (ISO) working group on anthropomorphic test devices: ISO/TC22/SC12/WG5. From 2001 to mid-2002, the first prototype of the WorldSID was subjected to an extensive worldwide evaluation programme at research institutes, government agencies and industry test laboratories around the world. The initial testing resulted in the highest ISO biofidelity rating for any mid-sized male side impact dummy to date along with some suggestions for further biofidelity refinements.

These identified refinements have been developed and incorporated into a revised version of the WorldSID prototype dummy, which has been subjected to another series of worldwide evaluation tests in order to assess the resulting biofidelity rating according to the requirements of ISO Technical Report 9790.

This paper presents and discusses the design modifications implemented in the revised WorldSID prototype dummy and its superior performance during the second round of biofidelity testing. The biofidelity rating of the WorldSID according to ISO TR 9790 and its response repeatability in the biomechanical tests will be addressed and compared with existing mid-sized male side impact dummies. The revised WorldSID prototype has exceeded the overall and individual body region biofidelity ratings of the first prototype. The revised prototype biofidelity rating is anticipated to be 7.3 with minor modifications to the dummy head that were underway at the time of writing this paper.

BACKGROUND

Five different 50th percentile male side impact dummies, DOT-SID, SID-HIII, EUROSID 1, ES-2 and BioSID are currently available for vehicle regulatory and development testing purposes. According to the International Organisation for Standardisation Technical Report 9790 (ISO TR 9790) [1] classification, which can be seen in Table 1, the biofidelity rating of all of these dummies lies in the "unacceptable" to "fair" ranges. The necessity of harmonising and improving the biofidelity of side impact dummies is therefore obvious.

Table 1.
ISO Biofidelity Classification

Excellent	> 8.6 to 10
Good	> 6.5 to 8.6
Fair	> 4.4 to 6.5
Marginal	> 2.6 to 4.4
Unacceptable	0 to 2.6

A new, advanced 50th percentile male side impact dummy has been developed in the form of the WorldSID within a task group comprised of dummy and biomechanics experts from the automotive industry, government agencies and research institutes from around the world. The objective of the WorldSID project is to develop a harmonised mid-sized male side impact dummy that meets the “good” to “excellent” classification on the ISO scale and launch the production dummy in March 2004. At that time, the dummy design will be put into the public domain, and will be available for use in regulatory test procedures, including those to be defined by the **I**nternational **H**armonized **R**esearch **A**ctivities (**IHRA**), and also for all other test procedures.

INTRODUCTION

The performance of the first and only WorldSID prototype (Figure 1) was verified during its debut in December 2000 in full-scale crash and sled tests. The initial WorldSID dummy design and test results were published at the Enhanced Safety of Vehicle Conference (ESV) 2001 [2], [3].

The dummy was subsequently subjected to a comprehensive test programme to determine its compliance with ISO TR 9790. The results of the first round of ISO TR 9790 tests were published at the Stapp Car Crash Conference 2001 [4]. Based on those results, it was apparent that the ratings of some body regions, namely the pelvis, shoulder and neck required improvements.

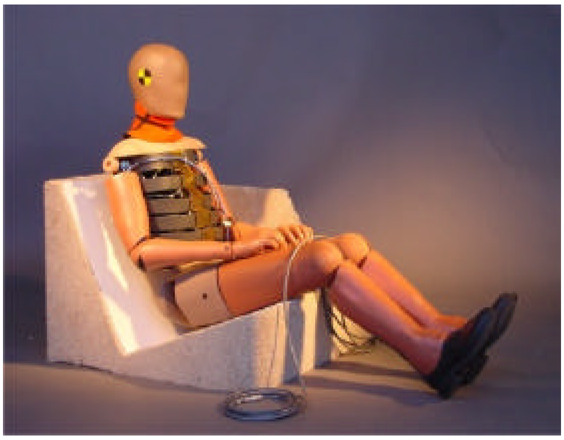

Figure 1. The WorldSID prototype dummy

Further tests were conducted to enhance the biofidelity of the pelvis and shoulder. These tests were conducted within the European Commission's **SIBER** (**S**ide **I**mpact Dummy **B**iomechanics and **E**xperimental **R**esearch) project. The results of this testing lead to some of the modification described below. The prototype dummy was then upgraded with these modifications. This revised prototype dummy was then subjected to a second round of TR9790 testing to evaluate the effects of the changes.

DESIGN MODIFICATIONS OF THE REVISED PROTOTYPE

Biofidelity analysis of the ISO TR 9790 tests conducted on the WorldSID prototype revealed that the goal of a "good" biofidelity rating for the thorax and the abdomen was already achieved with the first prototype. The neck, shoulder and pelvis required revision of their components.

Neck

The data from the ISO neck tests conducted on the prototype dummy indicated that the neck was globally too soft [4]. It was speculated that the low rating was mainly due to the original shoulder design being too soft. So no modifications were made to the neck of the revised WorldSID prototype dummy.

Shoulder

The WorldSID prototype shoulder was determined to be too soft during the initial biofidelity tests [4]. This was indicated by high deflection responses, whereas the pendulum forces that were generated met or slightly exceeded the corridor. The challenge was to reduce deflection without increasing the force. The thickness of the shoulder rib damping material was increased from 4 mm to 9 mm (Figure 2). Additionally the durometer of the shoulder plug was changed to reduce the impact force. A rib stop was installed to prevent the shoulder rib from bottoming out and damaging the rib and instrumentation.

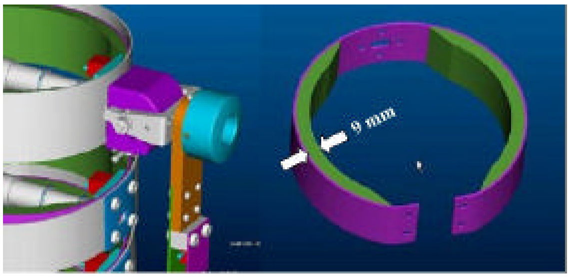

Figure 2. Shoulder rib.

Pelvis

The results of the initial biofidelity tests conducted on the pelvis revealed that it was too stiff [4]. It was determined that too much mass of the thigh was involved in the pelvis impact and excessive left to right mass coupling was occurring in the pelvis itself.

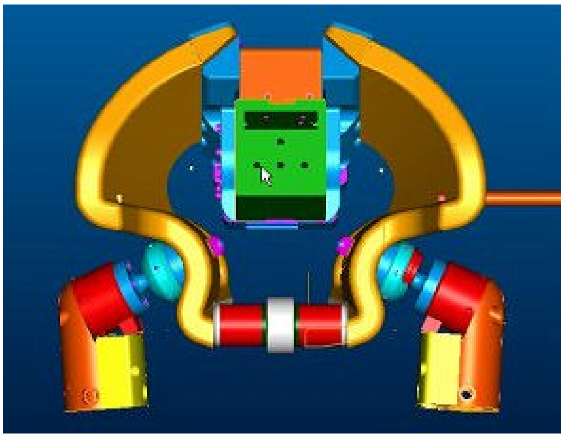

Figure 3. Redesigned pelvic bone with decoupled pubic area

To correct these issues, the pelvic bone material in the revised prototype dummy is softer and the pubic symphysis load cell was reduced in size and fitted between soft rubber bumpers (Figure 3).

Lower Extremities

It was seen during the prototype testing that there was a significant influence of the femur to flesh mass distribution in the pelvis responses during impact testing. The overall femur mass in the prototype dummy corresponded well with the **U**niversity of **M**ichigan **T**ransportation **R**esearch **I**nstitute (**UMTRI**) target [5], but the ratio of bone to flesh mass was incorrect. This was due to the large amount of instrumentation that was housed in the femur bones.

Figure 4. Revised prototype femur heavy flesh and light bone

The upper legs were modified to best achieve the UMTRI targets for mass distribution between the femur bone and flesh. The femur bone was lightened by changing the material from steel to aluminium and removing one femur load cell. Other measures for reducing the weight included lightening holes in the knee and femur neck, reducing the kneecap thickness and increasing the knee flesh (Figure 4). Additional bone mass reduction was achieved by removing the Data Acquisition Systems (DAS) housing from the femur and mounting the DAS modules in cavities in the flesh. The flesh mass was increased by changing from vinyl-covered foam to a solid vinyl assembly. Additionally, the new flesh would only be in contact with the lower end of the bone, resulting in a certain degree of decoupling between the bone and flesh.

BIOFIDELITY RATING AND REPEAT-ABILITY ANALYSIS

The WorldSID was specified to meet the biofidelity targets defined by the ISO TR 9790 and also any future specifications recommended by the IHRA Biomechanics working group. The WorldSID Task Group is awaiting the publication of recommendations for biofidelity requirements from this group and will take those into consideration as soon as available. In accordance with the WorldSID specification, the ISO TR 9790 biofidelity rating procedures were used to quantify individual body regions and overall dummy biofidelity.

The ISO TR 9790 tests conducted with the WorldSID prototype dummy were repeated with the revised WorldSID prototype dummy. As with the prototype, Head Test 2 (drop test), Thorax Test 4 (drop test), and Pelvis Test 5, 6 (drop tests) and 9 (sled test), were not conducted since the required padding is no longer available. Additionally, the neck flexion and extension tests were not conducted. Three repeats were conducted of each test mode to determine the repeatability of the measurements and body regions.

ISO has defined the biofidelity rating as follows:

$$B_i = \frac{(\sum_j V_{i,j} (\sum_k W_{i,j,k} R_{i,j,k})) / \sum_k W_{i,j,k}}{\sum_j V_{i,j}} \quad \text{where}$$

- B_i is the body region biofidelity rating,
- $V_{i,j}$ is the weighting factor for each test condition for a given body region,
- $W_{i,j,k}$ is the weighting factor for each response measurement for which a requirement is given,
- $R_{i,j,k}$ is the rating of how well a given response meets its requirement ($R_{i,j,k}$ is equal to 10 if the response meets the requirement, 5 if the response is outside but lies within one corridor width of the requirement and 0 if neither of the previous is met),
- i represents the body region,
- j represents the test condition for a given body region i,
- k represents the response measurement for a given test condition j and a body region i.

The overall biofidelity is given by:

$$B = \frac{\sum_{i=1\,to\,6} U_i B_i}{\sum_{i=1\,to\,6} U_i}$$

where

- U_i is the weighting factor for each body region,
- i = 1 to 6, respectively representing the head, the neck, the shoulder, the thorax, the abdomen and the pelvis.

The value of a specific response measurement rating was calculated by averaging the ratings determined for this measurement in each test conducted under the same conditions. When tests were conducted on both sides of the dummy, an average of all measurements including the left and the right side values were used to determine the measurement rating.

A repeatability analysis is conducted using the coefficient of variation (CV) method. The CV is defined as the standard deviation of the samples divided by the sample mean, and is expressed as a percentage. The repeated responses, which have a CV of 3% or less, are commonly considered as having an excellent level of repeatability, whilst a value of 10% and above is considered to have a poor level of repeatability. The WorldSID specification is to have a CV of less than 7%. The repeatability analysis was only performed if three or more results were available for measurements collected under the same test condition.

BIOFIDELITY RESULTS AND REPEAT-ABILITY

Head Biofidelity and Repeatability

One of the two head tests specified in ISO TR9790 was carried out with the revised WorldSID prototype for lateral assessment.

Head Test 1, according to Hodgens and Thomas [6], is a 200 mm drop test onto a rigid surface with the head only.

The data for this test are contained in Appendix A, Table A1. The peak resultant accelerations for the none-struck side head were above the 150 g upper limit. The biofidelity rating for Head Test 1 is 5.

Since only Head Test 1 could be carried out, the overall head biofidelity rating is 5, the ISO biofidelity classification is “fair” and the repeatability (0.09%) is excellent (Table 2).

Table 2.
Head Biofidelity Rating and CV

Response Measurements	k	$W_{1,1,k}$	$R_{1,1,k}$	CV (%)
Peak Resultant Acceleration	1	9	5	0.09
Head Biofidelity Rating B1			**5**	

During the course of writing this manuscript it was discovered that a processing error had occurred with the first round of prototype head test data. The data previously presented were approximately 115 g's, which corresponded to a biofidelity rating of 10 for the head. Using the corrected processing, the head results were actually 166 g's, which correspond to a rating of 5. The previous overall dummy biofidelity rating was reported as 6.5, but should have been reported as 5.7.

Neck Biofidelity and Repeatability

Three different sled tests were conducted to determine the lateral biofidelity of the dummy neck. The data from these tests are contained in Appendix B, Tables B1 through B3. All neck tests were conducted without the neck shield, since it was previously determined that the neck shield had no influence on the neck biofidelity performance [4]. Only left side impacts were conducted.

Neck Test 1 is a sled test based on the volunteer tests conducted by Ewing et al. [7]. The requirements derived from these tests originate from the analysis performed by Wismans et al. [8]. The mean sled velocity was 6.9 m/s and average sled deceleration was 7.2 g. Boundaries were given for longitudinal acceleration and displacement at T1, longitudinal and vertical head CG displacement relative to T1, the time of peak head excursion, lateral and vertical peak head acceleration, the peak lateral flexion angle and the peak twist angle.

The Neck Test 1 data are contained in Appendix B, Table B1. In three tests, the revised prototype's T1 horizontal acceleration and displacement responses were within the limits and achieved ratings of 10. All of the other measurements achieved ratings between 5 and 10, with the exception of the peak neck twist angle, which achieved a rating of 0. The individual measurement ratings, the overall Neck Test 1 rating and the CV of the measurements can be seen in Table 3.

Table 3.
Neck Test 1 Biofidelity Ratings and CV

Response Measurements	k	$W_{2,1,k}$	$R_{2,1,k}$	CV (%)
Peak T1Hor. Acceleration	1	5	10	8
Peak T1 Hor. Displacement	2	5	10	7
Peak Hor. Displacement of the Head C.G. Relative to T1	3	8	6.7	7
Peak Vertical Displacement of the Head C.G. Relative to T2	4	6	5	7
Time of Peak Head Excursion	5	5	6.7	2
Peak Lateral Acceleration of the Head	6	5	10	n.d.
Peak Vertical Acceleration of the Head	7	5	5	n.d.
Peak Flexion Angle	8	7	8.3	3
Peak Twist Angle	9	4	0	9
Neck Test 1 Rating			**7**	

As in the case of the prototype, the results achieved with the revised prototype were somewhat contradictory. The responses of the peak head C.G. displacement with respect to T1 are low, and the peak lateral accelerations of the head are high. This indicates that the neck is too stiff in the lateral direction. However, the peak flexion angle is at the upper corridor and actually exceeds it in one test, indicating that the neck is soft.

The Neck Test 1 biofidelity rating is 7.0, which is considerably better than 4.3 from the prototype.

Neck Test 2 is a sled test configuration referring to Patrick and Chou tests [9]. The sled velocity was 5.8 m/s and the constant deceleration level was 6.7 g. From this test, boundaries for peak flexion angle, peak forces and moments at the occipital condyles and peak head resultant acceleration were given.

The results of Neck Test 2 can be found in Appendix B, Table B2. The peak flexion angle for Neck Test 2 lies on or above the upper boundary and most of the moments and forces lie below the lower boundary. This indicates that the neck is soft.

Neck Test 2 biofidelity rating is 2.4, which is comparable with that of the prototype (2.5). The ratings and the CV values for this test are shown in Table 4.

Table 4.
Neck Test 2 Biofidelity Ratings and CV

Response Measurements	k	$W_{2,2,k}$	$R_{2,2,k}$	CV (%)
Peak Flexion Angle	1	7	6.7	6
Peak Bending Moment about A-P Axis at O.C.	2	7	1.7	5
Peak Bending Moment about R-L Axis at O.C.,	3	3	5	8
Peak Twist Moment	4	4	1.7	7
Peak Shear Force at O.C.	5	7	0	6
Peak Tension Force at O.C.	6	6	0	5
Peak P-A Shear Force	7	3	0	5
Peak Resultant Head Acceleration	8	4	5	6
Neck Test 2 Rating			**2.4**	

Neck Test 3 is the configuration established by Tarriere et al. [10] based on a single cadaveric test with an initial velocity of 6 m/s and sled deceleration of 12.2 g. Boundaries are given for peak lateral T1 acceleration, peak lateral head C.G. acceleration, peak horizontal displacement of the head CG relative to the sled, peak flexion angle and peak twist angle.

Table 5.
Neck Test 3 Biofidelity Ratings and CV

Response Measurements	k	$W_{2,3,k}$	$R_{2,3,j}$	CV (%)
Peak Lateral Acceleration of T1, A_y	1	5	6.7	7
Peak Head C.G. Lateral Acceleration, A_y	2	5	n.a.	n.d.
Peak Head C.G. Horizontal Displacement, D_y	3	8	10	1
Peak Flexion Angle, q_x	4	7	6.7	4
Peak Twist Angle, q_z	5	4	0	5
Neck Test 3 Rating			**6.7**	

The data of the Neck Test 3 series are shown in Appendix B, Table B3. The peak lateral acceleration of T1 lies on or above the upper boundary, whereas the data for the peak head acceleration were lost. The peak head horizontal displacement is within the corridors, whilst the peak head flexion angle lies on or above the upper boundary. Thus indicating that the neck is soft.

The Neck Test 3 biofidelity rating for the revised prototype is 6.7 compared to 4.3 for the prototype.

The ratings and the CV values for this test are shown in Table 5.

Overall Neck Biofidelity Rating: The overall neck biofidelity ratings and repeatability are shown in Table 6. The overall neck biofidelity rating of the revised WorldSID prototype is 5.2, which corresponds to an ISO classification of “fair”. This is an improvement to that of the prototype dummy (3.6). The increase in the biofidelity rating is attributed to modifications made to the shoulder area, since the neck design was not changed. The overall neck repeatability meets the specification.

Table 6.
Overall Neck Biofidelity

	j	$V_{2,j}$	$R_{2,j}$
Neck Test 1	1	7	7
Neck Test 2	2	6	2.4
Neck Test 3	3	3	6.7
Neck Biofidelity Rating B2		**5.2**	

As in the case of the prototype, the entire neck still appears too soft when subjected to lateral impacts. The stiffness of the neck may be increased for the pre-production dummy, to better meet the biofidelity specification.

Shoulder Biofidelity

All four ISO TR 9790 shoulder tests were conducted on the WorldSID revised prototype. These tests include one pendulum impact and three sled tests.

Shoulder Test 1 involves an APR-type pendulum impacts using a 23.4 kg pendulum with a 150 mm cylindrical impact face [11]. Targets are given for the impactor force/time history and the maximum shoulder deflection.

Table 7.
Shoulder Test 1 Biofidelity Ratings and CV

Response Measurements	k	$W_{3,1,k}$	$R_{3,1,j}$	CV (%)	
				left	right
Pendulum Force	1	8	5	1	0.9
Peak Shoulder Deflection	2	6	7.5	2	3
Shoulder Test 1 Rating			**6.1**		

The Shoulder Test 1 data are in Appendix C, Table C1, Figures C1 and C2. The peak shoulder deflection response falls within the corridors for the left side impacts and lies within one corridor width below the lower boundary for the right side impacts. The pendulum forces exceed the upper corridor limit, but lie within one corridor width for both the right and left side impacts, and therefore have a rating of 5. The time history of the pendulum force measurements is similar to the requirements.

Shoulder Test 1 biofidelity rating was improved from 5.7, in the prototype dummy, to 6.1 in the revised prototype. The biofidelity ratings and CV values for Shoulder Test 1 are in Table 7. The repeatability for this test is “excellent”.

Shoulder Test 2 is the 7.2 g sled test configuration described under Neck Test 1. Targets are given for peak horizontal T1 acceleration and peak horizontal T1 displacement. Only left side tests were conducted.

The revised prototype responses are well within their prescribed corridors. Consequently, the rating for this test is 10 (Table 8), which is a significant improvement when compared with a rating of 5 for the prototype dummy. The test data can be seen in Appendix C, Table C2.

Table 8.
Shoulder Test 2 Biofidelity Ratings and CV

Response Measurements	k	$W_{3,2,k}$	$R_{3,2,j}$	CV (%)
Peak T1 Horizontal Accelereation A_y	1	6	10	8
Peak T1 Horizontal Displacement	2	6	10	7
Shoulder Test 2 Rating			**10**	

Shoulder Test 3 is the 12.2 g sled test configuration described under Neck Test 3. The peak lateral accelerations of T1 are taken into consideration in this test.

The Shoulder Test 3 data are contained in Appendix C, Table C3. The peak T1 lateral acceleration data are within or just above the upper boundary for the revised prototype dummy. This has produced a slightly improved rating of 6.7 for the revised prototype dummy when compared to a rating of 5 for the prototype dummy. The ratings and CV values for Shoulder Test 3 are Table 9.

Table 9.
Shoulder Test 3 Biofidelity Rating and CV

Response Measurements	k	$W_{3,3,k}$	$R_{3,3,k}$	CV (%)
Peak T1 Lateral Accelereation A_y	1	6	6.7	7
Shoulder Test 3 Rating			**6.7**	

Shoulder Test 4 requirements are derived from tests performed at the Wayne State University and analysed by Irwin et al. [12]. The sled velocity is 8.9 m/s. This test only requires responses for the thorax and shoulder plate forces.

Table 10.
Shoulder Test 4 Biofidelity Rating and CV

Response Measurements	k	$W_{3,4,k}$	$R_{3,4,k}$	CV (%) 15psi	CV (%) 23psi
Shoulder and Thoracic Plate Force	1	6	5	7	1
Shoulder Test 4 Rating			**5**		

The measurement data can be found in Appendix C, Figure C3. The peak force response of the revised prototype lies slightly below the lower boundary, and the duration of the dummy response are slightly greater than that of the corridors. The biofidelity rating for Shoulder Test 4 for both the prototype dummy and revised prototype dummy are 5.0 (Table 10).

Overall Shoulder Biofidelity Rating: The shoulder stiffness was increased on the basis of the prototype dummy test results previously published [4]. These modifications achieved the desired effect, with the overall shoulder biofidelity rating of the WorldSID revised prototype at 6.7 (Table 11).

Table 11.
Overall Shoulder Biofidelity

	j	$V_{3,j}$	$R_{3,j}$
Shoulder Test 1 Rating	1	6	6.1
Shoulder Test 2 Rating	2	5	10
Shoulder Test 3 Rating	3	3	6.7
Shoulder Test 4 Rating	4	7	5
Shoulder Biofidelity B3		**6.7**	

This is equivalent to a biofidelity classification of "good". It is also a significant improvement over the prototype rating of 5.2.

Thorax Biofidelity

Five different tests were performed on the revised WorldSID dummy thorax to determine the thorax biofidelity rating. These tests included two pendulum tests, a drop test and two sled tests.

Thorax Test 1 is a pendulum test, in which a 15 kg, rigid impactor with a diameter of 150 mm impacts onto the thoracic ribs, with the arms in a horizontal position, at 4.3 m/s [13].

Three repeat tests were performed on the left and right side of the dummy's thorax. The measurement data are contained in Appendix D, Figures D1 to D4. In all runs, the pendulum force was within the corridors, and is rated as 10. The upper spine acceleration data are within one corridor width of the upper bound. This gives a rating of 5 for the upper spine acceleration.

Table 12.
Thorax Test 1 Biofidelity Ratings and CV

Response Measurements	k	$W_{4,1,k}$	$R_{4,1,k}$	CV (%) left	CV (%) right
Pendulum Force	1	9	10	0.4	3
Upper Spine Lateral Acceleration	2	7	5	4	5
Thorax Test 1 Rating			**7.8**		

Thorax Test 1 revealed an improved rating of 7.8 in comparison with the prototype (5.9). The repeatability meets the specification (Table 12).

Thorax Test 2 is the same configuration as Thorax Test 1, except that the impact speed is 6.7 m/s [14]. Targets are only given for the pendulum impact force.

Table 13.
Thorax Test 2 Biofidelity Rating and CV

Response Measurements	k	$W_{4,2,k}$	$R_{4,2,k}$	CV (%) left	CV (%) right
Pendulum Force left side	1	9	10	0.8	2
Thorax Test 2 Rating			**10**		

The measurements for left and right side impacts (Appendix D, Figure D5 and D6) lie within the corridor, giving Thorax Test 2 a rating of 10 with an excellent repeatability (Table 13). The prototype rating for Thorax Test 2 was also 10.

Thorax Test 3 consists of dropping the dummy laterally from a height of 1m onto a continuous, rigid plate which spans the shoulder, thorax and abdomen regions, with a separate plate for the pelvis region. The arm is rotated 20° forward of the dummy's thoracic spine [15]. Targets are given for the thoracic plate force and peak rib deflection.

The biofidelity rating for Thorax Test 2 conducted on the revised WorldSID dummy is 7.9 (Table 14). The rating for the prototype dummy was 7.1.

The data are in Appendix D, Table D1, Figures D7 and D8. The thoracic plate force responses of the revised prototype met the corridor for the left side, but were within one corridor width for the right side tests. The peak thoracic rib deflection responses lie on or just above the upper boundary except for one run, where it lies on the lower boundary.

Table 14.
Thorax Test 3 Biofidelity Ratings and CV

Response Measurements	k	$W_{4,3,k}$	$R_{4,3,k}$	CV (%) left	CV (%) right
Thorax Plate Force	1	8	7.5	3.0	9.0
Peak Deflection of the Impacted Rib	1	8	8.3	5.0	20.0
Thorax Test 3 Rating			**7.9**		

Thorax Test 5 requires a Heidelberg-type rigid wall sled impact at 6.8 m/s [16]. Three repeat left side impacts were conducted.

The measurements are given in Appendix D, Table D1 and Figure D9. The thoracic plate forces are within the corridor for all tests. Two of the peak T1 accelerations are within one corridor width of the lower boundary and the third exceeds one corridor width. The peak T12 accelerations lie within one corridor width below the lower limit, whereas the peak lateral accelerations of the impacted rib are within the corridor. The Thorax Test 5 biofidelity rating for the revised prototype is 7.1, whereas the prototype rating was 5.8 (Table 15).

Table 15.
Thorax Test 5 Biofidelity Ratings and CV

Response Measurements	k	$W_{4,5,k}$	$R_{4,5,k}$	CV (%)
Thorax Plate Force	1	8	10	n.d.
Peak Lateral Acceleration of the Upper Spine	2	7	3.3	6
Peak Lateral Acceleration of the Lower Spine	3	7	5	11
Peak Lateral Acceleration of the Impacted Rib	4	6	10	18
Thorax Test 5 Rating			**7.1**	

Thorax Test 6 is a WSU-type padded load plate wall configuration with padding of 15 psi and 23 psi [17]. The dummy is seated on the sled with its arms 45° forwards from the vertical, and the sled is decelerated at an impact speed of 8.9 m/s.

Thorax Test 6 data are in Appendix D, Figure D10. The thoracic plate force data lie within one corridor width below the lower boundary and therefore are rated 5.0 (Table 16).

Table 16.
Thorax Test 6 Biofidelity Rating and CV

Response Measurements	k	$W_{4,6,k}$	$R_{4,6,k}$	CV (%) 15psi	CV (%) 23psi
Shoulder + Thoracic Plate Force	1	9	5	5	1
Thorax Test 6 Rating			**5**		

The biofidelity rating of the revised prototype and the prototype dummy for Thorax Test 6 were both 5.0.

Overall Thorax Biofidelity Rating: The revised WorldSID prototype overall thorax biofidelity rating is 7.7 (Table 17) which is an improvement from the previous prototype dummy testing (6.9).

Table 17.
Overall Thorax Biofidelity

	j	$V_{4,j}$	$R_{4,j}$
Thorax Test 1 Rating	1	9	7.8
Thorax Test 2 Rating	2	9	10
Thorax Test 3 Rating	3	6	7.9
Thorax Test 5 Rating	5	7	7.1
Thorax Test 6 Rating	6	7	5
Thorax Biofidelity B4		**7.7**	

This corresponds to an ISO classification of "good". The improvement in the thorax biofidelity rating is due to a combination of the ribs softening due to excessive testing and modifications to the shoulder and pelvis regions.

Abdomen Biofidelity and Repeatability

To determine the overall abdomen biofidelity of the revised WorldSID prototype dummy, five different abdominal tests were performed. These tests consist of two drop tests and three sled tests.

Abdomen Test 1 is a lateral drop test from a height of 1 m onto a simulated armrest, which protrudes 41 mm above a continuous, rigid plate. The plate spans the shoulder, thorax and abdomen regions, with a separate plate for the pelvis region. The arm is removed from the dummy [11].

The data are in Appendix E, Table E1 and Figures E1 and E2. The peak armrest force is within the corridors for the left side runs. The duration of the peak armrest force data slightly exceeds the corridor, but far less than the prototype. As the shape is very similar to the corridor and time zero is very difficult to determine in drop tests, it was agreed to rate this response as 10. The right side responses also met the corridor in terms of peak values, but exceeded the duration more and are rated as 5 The T12 accelerations are all within their prescribed corridors and are rated 10. Three abdominal rib accelerations are within one corridor width of the lower corridor and three exceed one corridor width. In all six tests, the requirement was met for the rib displacements (Table 18).

Table 18.
Abdomen Test 1 Biofidelity Ratings and CV

Response Measurements	k	$W_{5,1,k}$	$R_{5,1,k}$	CV (%) left	CV (%) right
Armrest Force	1	9	7.5	5	4
Peak Acceleration of the Lower Spine	2	6	10	4	5
Peak Acceleration of the Impacted Rib	3	4	2.5	3.1	7
Peak Abdomen Penetration	4	9	10	3.9	4.5
Abdomen Test 1 Rating			**8.1**		

The biofidelity rating for the revised prototype for Abdomen Test 1 is 5.7 compared to a rating of 7.0 for the prototype.

Abdomen Test 2 is the same as test 1, except that the drop height is 2 m [11].

Due to the severity of this test and the fact that the ribs have been exposed to over 400 tests, the dummy ribs bottomed out during this test. Unfortunately, this made the data unusable.

Abdomen Test 3 is a WSU-type rigid wall sled test where the sled is accelerated until it reaches a velocity of 6.8 m/s. The brakes are then applied and the dummy slides into the rigid wall [17]. The dummy is seated on the sled with its arm at 45° forwards from the vertical.

Table 19.
Abdomen Test 3 Biofidelity Rating and CV

Response Measurements	k	$W_{5,,j,k}$	$R_{5,j,k}$	CV(%)
Abdominal Plate Force	1	9	8.3	8
Abdomen Test 3 Rating			**8.3**	

The measurement data are contained in Appendix E, Figure E3. In two runs the abdomen plate forces lie within the corridor and just below it in one run.

The biofidelity rating for Abdomen Test 3 is 8.3 for the revised prototype and was 10 for the prototype dummy (Table 19).

Abdomen Tests 4 is the same as Abomen Test 3, except that the sled velocity is 8.9 m/s [17].

The measurement data are contained in Appendix E, Figure E4. In all three tests, the abdomen plate forces for the Abdomen Test 4 lie within one corridor width below the lower boundary, and have a rating of 5 (Table 20).

Table 20.
Abdomen Test 4 Biofidelity Rating and CV

Response Measurements	k	$W_{5,,j,k}$	$R_{5,j,k}$	CV(%)
Abdominal Plate Force	1	9	5	6
Abdomen Test 4 Rating			**5**	

The biofidelity rating for Abdomen Test 4, for both the revised prototype and prototype dummies are 5.0.

Abdomen Test 5 is identical to Abdomen Test 4, except that the rigid wall is covered with paper honeycomb padding of 15 psi and 23 psi, respectively [17].

In the six tests conducted, the peak values for abdominal plate force (Appendix E, Figure E5) lie around the lower boundary, and the duration is slightly too long, resulting in a rating of 5 for this response (Table 21).

The biofidelity rating for Abdomen Test 5, for both the revised prototype and prototype dummies are 5.0.

Table 21.
Abdomen Test 5 Biofidelity Rating and CV

Response Measurements	k	$W_{5,5,k}$	$R_{5,5,k}$	CV(%) 15psi	CV(%) 23psi
Abdominal Plate Force	1	9	5	6	5
Abdomen Test 5 Rating			**5**		

Overall Abdomen Biofidelity Rating: The revised WorldSID prototype overall abdomen biofidelity rating is 6.6 (Table 22) which is an improvement from the previous prototype dummy testing (6.3). The revised prototype dummy rating corresponds to an ISO classification of “good”.

Even though the classification is now in the "good" category, the abdomen ribs are too soft. This was shown when abdomen test 2 was conducted and the ribs bottomed out. This was not the case in the prototype testing, when the ribs were new.

Table 22.
Overall Abdomen Biofidelity

	j	$V_{5,j}$	$R_{5,j}$
Abomen Test 1 Rating	1	7	8.1
Abomen Test 3 Rating	3	3	8,3
Abomen Test 4 Rating	4	3	5
Abomen Test 5 Rating	5	7	5
Abdomen Biofidelity B5		**6.6**	

Pelvis Biofidelity

Ten out of thirteen ISO TR 9790 pelvis tests were carried out with the WorldSID revised prototype. Tests 5, 6 and 9 were not carried out, as the corresponding padding was unavailable.

Pelvis Test 1 involves a rigid pendulum impact at 6 m/s. The impactor is defined as a 10 kg rigid impactor with a 600 mm radius of curvature and an outer diameter of 127 mm [19], [20], [21].

The measurement data are in Appendix F, Figure F1. The pendulum forces in the left side impacts lie just below the lower corridor and for the right side impacts are within the corridors. This gives ratings of 5 and 10, respectively (Table 23).

Table 23.
Pelvis Test 1 Biofidelity Rating and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%) left	CV(%) right
Pendulum Force Test	1	9	7.5	2	2
Pelvis Test 1 Rating			**7.5**		

The biofidelity rating for Pelvis Test 1 is 7.5 and has "excellent" repeatability with CV´s of 2%. This is an improved biofidelity rating when compared to the previous testing on the prototype dummy, which produced a rating of 5.0 for this test.

Pelvis Test 2 configuration is equivalent to Pelvis Test 1, but with an impact speed of 10 m/s [19], [20], [21]. Due to previous facility restrictions, Pelvis Test 2 was not carried out with the prototype dummy.

The data are in Appendix F, Figure F2. All of the pendulum force data are within the corridors, corresponding to a rating of 10.

Pelvis Test 2 biofidelity rating is 10 and the repeatability meets the specification for both sides of the dummy (Table 24).

Table 24.
Pelvis Test 2 Biofidelity Rating and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%) left	CV(%) right
Pendulum Force Test	1	9	10	6	2
Pelvis Test 2 Rating			**10**		

Pelvis Test 3 consists of dropping the dummy laterally from a height of 0.5 m onto a continuous, rigid plate which spans the shoulder, thorax and abdomen regions, with a separate plate for the pelvis region. The arm is rotated 20° forward of the dummy's thoracic spine [10]. Three tests were performed on each side of the dummy.

The data are in Appendix F, Table F1. The peak pelvis accelerations ilie within one corridor width below the lower boundary, corresponding to a rating of 5, the repeatability meets the specification (Table 25).

Pelvis Test 3 biofidelity rating for the revised prototype is 5 compared to a rating of 7.5 for the prototype.

Table 25.
Pelvis Test 3 Biofidelity Rating and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%) left	CV(%) right
Peak Pelvis Acceleration	1	7	5	6	5
Pelvis Test 3 Rating			**5**		

Pelvis Test 4 is the same as Pelvis Test 3, but with a dropping height of 1 m. [10].

Table 26.
Pelvis Test 4 Biofidelity Rating and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%) left	CV(%) right
Peak Pelvis Acceleration	1	7	3.3	6	6
Pelvis Test 4 Rating			**3.3**		

The data are in Appendix F, Table F1. Four responses lie within one corridor width below the lower boundary and two responses exceed one corridor width. Again, the repeatability meets the specification. The corresponding ratings and CV´s are listed in Table 26.

The biofidelity rating of the revised prototype for Pelvis Test 4 is 3.3 compared to 7.5 of the prototype

Pelvis Test 7 requires a Heidelberg-type rigid wall sled impact at 6.8 m/s [16].

The data are in Appendix F, Table F1. The peak pelvis plate forces determined are within the corridors. This corresponds to a rating of 10, which is a significant improvement from the prototype (0). The pelvis acceleration were below the lower boundary and are rated 5. The repeatability of the measurements meets the specification. The rating in this case is 5. The ratings and CV´s are listed in Table 27.

Table 27.
Pelvis Test 7 Biofidelity Ratings and CV

Response Measurements	k	$W_{6,7,k}$	$R_{6,j,k}$	CV(%)
Peak Pelvis Force	1	9	10	5
Peak Pelvis Acceleration	2	7	5	3
Pelvis Test 7 Rating			**7.8**	

The Pelvis Test 7 biofidelity rating of 7.8 for the revised prototype is greater than the prototype rating (3.6).

Pelvis Test 8 is the same as Pelvis Test 7, but it is conducted at 8.9 m/s [16].

The data are in Appendix F, Table F1. Only one test was conducted at this speed due to test severity. The pelvis acceleration data collected were within the corridors. Due to instrumentation problems, the load data was not collected. The pelvis acceleration rating is 10 (Table 28).

Table 28.
Pelvis Test 8 Biofidelity Ratings and CV

Response Measurements	k	$W_{6,7,k}$	$R_{6,j,k}$	CV(%)
Peak Pelvis Force	1	8	n/a	n.d.
Peak Pelvis Acceleration	2	7	10	n.d.
Pelvis Test 8 Rating			**10**	

The Pelvis Test 8 biofidelity rating is 10 for the revised prototype and was 4.7 for the prototype.

Pelvis Test 10 requires a WSU-type rigid wall sled impact at 6.8m/s [18].

The data are in Appendix F, Table F1 and Figure F3. The pelvic plate force data for two tests lie within the corridors and one test exceeded the upper limit. For all tests, the pelvis acceleration responses lie within one corridor width below the lower boundary. The ratings and CV values are shown in Table 29.

Table 29.
Pelvis Test 10 Biofidelity Ratings and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%)
Pelvic Plate Force	1	9	8.3	0.8
Peak Pelvis Acceleration	2	7	5	12
Pelvis Test 10 Rating			**6.9**	

A biofidelity rating of 6.9 for the revised prototype for Pelvis Test 10 is a significant improvement over the prototype (4.1).

Pelvis Test 11 is a WSU-type rigid wall sled impact at 8.9 m/s [18].

The data are in Appendix F, Table F1 and Figure F4. The pelvis acceleration data are below the lower corridor and two of three force measurements exceed the upper corridor. This corresponds to a rating of 5 for the pelvis acceleration and 6.7 for the force data.

Pelvis Test 11 biofidelity rating is 5.9, which is below that of the prototype dummy (7.2). The repeatability of the revised prototype dummy in this test is excellent. The ratings and CV values are shown in Table 30.

Table 30.
Pelvis Test 11 Biofidelity Ratings and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%)
Pelvic Plate Force	1	9	6.7	0.5
Peak Pelvis Acceleration	2	7	5	1
Pelvis Test 11 Rating			**5.9**	

Pelvis Test 12 is a WSU-type padded wall sled impact at 89 m/s with a padding stiffness of 15 psi. 200 mm padding was used to prevent the pelvis from bottoming out the padding, as previously seen with the prototype dummy.

Table 31.
Pelvis Test 12 Biofidelity Ratings and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%)
Pelvic Plate Force	1	9	5	7
Peak Pelvis Acceleration	2	7	5	5
Pelvis Test 12 Rating			**5**	

The data are in Appendix F, Table F1 and Figure F5. The peak pelvis accelerations lie outside the tolerance range, corresponding to a rating of 5. The peak pelvic plate forces lie within the corridor, but the duration does not correspond entirely, resulting in a rating of 5. The repeatability meets the specification. The individual ratings are listed in Table 31.

The Pelvis Test 12 biofidelity rating for the revised prototype is 5.0 and was 0 for the prototype.

Pelvis Tests 13 is the same as Pelvis Test 12, but with a padding stiffness of 23 psi.

The data are listed in Appendix F, Table F1 and Figure F6. The pelvis accelerations were low, lying outside of one corridor width. The plate force data lie within the corridors. The repeatability meets the specification. The individual ratings and CV´s are listed in Table 32.

The Pelvis Test 13 biofidellity rating for the revised prototype (5.6) is similar to that of the prototype (5.7).

Table 32.
Pelvis Test 13 Biofidelity Ratings and CV

Response Measurements	k	$W_{6,j,k}$	$R_{6,j,k}$	CV(%)
Pelvic Plate Force	1	9	10	2
Peak Pelvis Acceleration	2	7	0	n.d.
Pelvis Test 13 Rating			**5.6**	

Overall Pelvis Biofidelity Rating: The redesigned pelvis led to the rating improving from 4.2 for the prototype dummy to 7.3 for the revised prototype. This meets the "good" specification (Table 33).

On the whole, the pelvis appears slightly soft. Its design will be slightly stiffer in the pre-production dummy.

Table 33.
Overall Pelvis Biofidelity

	j	$V_{6,,j}$	$R_{6,,j}$
Pelvis Test 1 Rating		8	7.5
Pelvis Test 2 Rating		9	10
Pelvis Test 3 Rating		4	5
Pelvis Test 4 Rating		4	3.3
Pelvis Test 7 Rating		8	7.8
Pelvis Test 8 Rating		7	10
Pelvis Test 10 Rating		3	6.9
Pelvis Test 11 Rating		3	5.9
Pelvis Test 12 Rating		3	5
Pelvis Test 13 Rating		7	5.6
Pelvis Biofidelity B6		**7.3**	

Overall Dummy Biofidelity

Taking the biofidelity rating for each body region and the corresponding factors into consideration, an overall biofidelity rating for the entire dummy was calculated to be 6.5. This exceeds the biofidelity rating of the prototype dummy (6.2) (Table 34).

The objectives of the WorldSID project are to produce a dummy where each body segment, and the entire dummy, has a "good" or "excellent" biofidelity classification. The shoulder, the thorax, the abdomen and the pelvis have achieved the "good" classification. The head and the neck biofidelity classifications are in the "fair" category.

The head skin needs to be thicker to reduce the accelerations of the head to achieve a classification of “good”. It is thought that the head should be easily tuneable to achieve a rating of 10, corresponding to the “excellent” classification. That would raise the overall biofidelity rating of the WorldSID revised prototype to 7.3 and a “good” classification, which would meet the biofidelity specifications (Table 34).

Table 34.
WorldSID Overall Biofidelity

Body Part	U_i	rev. prototype (head modification)	rev. prototype	prototype
Head	7	10	5	5
Neck	6	5.2	5.2	3.6
Shoulder	5	6.7	6.7	5.2
Thorax	10	7.7	7.7	6.9
Abdomen	8	6.6	6.6	6.3
Pelvis	8	7.3	7.3	4.2
WorldSID		**7.3**	**6.5**	**6.2**

The neck to be slightly stiffened to achieve a classification of “good”. Minor modifications to the material stiffness of the abdomen and pelvis are expected in the pre-production dummies, which will further improve their performance.

Overall Dummy Repeatability

Table 35 shows the ranges of the CV values for each body region.

The head had excellent repeatability of 0.09%. The neck and the shoulder have CV values in a range from 1% to 9% and 0.9% to 8%, respectively. The majority of the measurements for the neck and shoulder have CV values of 7% or less, wich meets the WorldSID specifications. The shoulder exhibits excellent repeatability in the pendulum tests. The latter is also valid for the most measurements derived from thorax pendulum tests with CV values from 0.4% to 5%. The CV values of four measurements, that exceed the 5% were observed in sled or drop tests. A portion of the increased variance may be attributed to the variation of these test modes. Most of the CV values for the adomen measurements are below the 7% specification for the WorldSID. Three measurements exceed this target. Two of those are derived from drop tests and one from a noisy data for the abdomen plate force in a sled test, and therefore is not attributed to the dummy. Twelve out of fourteen pelvis measurements show a repeatability of less than 7%. The two that exceed the 7%, are derived from sled tests and may be influenced by the variation of test set-up.

Table 35.
WorldSID Repeatability

Body Region	Coefficient of Variance, CV (%)
Head	0.09
Neck	1-9
Shoulder	0.9-8
Thorax	0.4-20
Abdomen	0.8-12
Pelvis	0.5-12

The repeatability of the production dummy will increase because its components will not be made individually by hand.

COMPARISION OF WORLDSID TO EXISTING 50th PERCENTILE MALE SIDE IMPACT DUMMIES

The revised WorldSID prototype is compared to the DOT SID [22], ES-2 [23] and BioSID [24] in Table 36. All of the ratings for each of these dummies are reported in Appendix G. The WorldSID revised prototype is the only dummy to obtain a "good" rating on the ISO biofidelity scale.

Table 36.
Biofidelity Comparison

	Biofidelity Rating						
	Head	Neck	Shoulder	Thorax	Abdomen	Pelvis	**Overall**
WorldSID with new head	10	5.2	6.7	7.7	6.6	7.3	**7.3**
WorldSID	5	5,2	6.7	7.7	6.6	7.3	**6.5**
BioSID	6,7	6,7	7,3	6,3	3,8	4	**5,7**
ES-2	5	4,4	5,3	5,2	2,6	5,3	**4,6**
DOT SID	0	2,5	0	3,1	4,4	2,5	**2,3**

The WorldSID revised prototype achieves the best overall dummy rating and also the best single body region ratings for the thorax, abdomen and pelvis. The head, neck and shoulder ratings are equivalent or better than the ES-2 and DOT SID. The modifications currently being made to the head will improve the WorldSID head rating to 10. This will then exceed the rating of the BioSID head (6.7). Only Neck Test 1 and 3 were conducted on the BioSID. For Neck Test 1, both the BioSID and the WorldSID achieved a rating of 7. For Neck Test 3, the WorldSID has a rating of 6.7 and the BioSID has a rating of 5.2. Considering only these two tests, the WorldSID neck rating exceeds the BioSID and all other neck ratings.

The ratings in Table 36 are corrected to non-normalized values for all dummies to enable a correct comparison. The DOT SID and BioSID ratings are different to those reported previously. Previously the DOT SID and BioSID data were normalized as recommended in an earlier version of ISO TR9790.

The NHTSA (**N**ational **H**ighway **T**raffic **S**afety **A**dministration) exposed the WorldSID prototype (dummy prior to biofidelity upgrades) together with two other side impact dummies, the ES-2 and the SID-HIII to a newly developed biofidelity ranking system called Bio Rank System, as reported by Rhule, H. et al. [25].

This system quantifies the ability of a dummy to load a sled wall as a cadaver does (External Biofidelity) and the ability of a dummy to replicate those cadaver responses that best predict injury potential (Internal Biofidelity). The ranking is based on the ratio of the cumulative variance of the dummy response relative to the mean cadaver response and the cumulative variance of the mean cadaver response relative to the mean plus one standard deviation. That ratio expresses how well a dummy duplicates a cadaver response. Contrary to the ISO rating system, the lower the rating value the better the biofidelity.

Although still under development and not in use by the international community, it can be seen, that this assessment system also showed the WorldSID prototype to have the best ranking out of the 3 tested dummies. It is anticipated that the revised WorldSID prototype dummy would do even better if subjected to the same test conditions as the SID-HIII and ES-2 dummies.

CONCLUSIONS

The WorldSID project is aimed at designing and manufacturing an advanced, globally harmonised side impact dummy with a biofidelity rating of "good" to "excellent" according to ISO TR 9790.

The very first prototype showed that this goal should be attainable. The design modifications considered necessary following the first biofidelity analysis were implemented. The revised prototype was then subjected to a second round of biofidelity tests. The design modifications were successful. The biofidelity rating for the revised prototype has been further improved (from 6.2 to 6.5). All body segments, with the exception of the head and the neck already exceed the specification of a classification of at least "good" in accordance with the ISO TR 9790 rating scale. The revised prototype biofidelity rating is anticipated to be 7.3 with minor modifications to the dummy head that were underway at the time of writing this article.

Compared with the current 50th percentile male side impact dummies, the overall WorldSID revised prototype's ratings are better than all others. It achieves by far the best overall rating, and is the only side impact dummy with an overall biofidelity rating of "good".

The dummy has now been used in over 400 crash, sled, pendulum and verification tests without suffering major damage. This also reveals the dummy's good durability. As a result of this extensive use, the ratings of certain body regions such as the abdomen and thorax may have changed independently of the design modifications, as these regions may have become softer due to extensive testing. This gives rise to the assumption that the pre-production dummies will lead to a further improvement in overall and single body region biofidelity ratings, merely due to the fact that these dummies will be new. In addition, the design of both the abdomen and the pelvis in the pre-production dummies may be slightly stiffer.

The analysis of the repeated test results indicates a good repeatability, meeting the specification of less than 7% for most of the measurements.

The CV values of some measurements exceeded the 7%. However, these measurements are derived in types of tests, which are generally considered to have a poor repeatability due to test set-up difficulty or padding variation. The CVs calculated for those tests may not accurately reflect the dummy repeatability, and may be to a certain amount a factor of the test repeatability.

Beginning in March 2003, a series of twelve pre-production dummies will be evaluated in biomechanical tests, and also in a multitude of sled, crash and verification tests throughout the world. Based on the biofidelity, repeatability, reproducibility and durability results, the completion of the side impact dummy with the highest level of biofidelity in the world, the WorldSID, can be anticipated to be ready for the release into the public domain in March 2004.

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REFERENCES

1. ISO/TC22/SC12/WG5, Technical Report 9790 – Road Vehicles – Anthropomorphic side impact dummy – lateral impact response requirements to assess the biofidelity of the dummy, 2000

2. Scherer, R. et. al. , Design and evaluation of the WorldSID prototype dummy, Proceedings of the 17th ESV Conference, paper No. 409, 2001

3. Page, M. et. al., Performance of the prototype WorldSID dummy in side impact crash tests, Proceedings of the 17th ESV Conference, paper No. 482, 2001

4. Cesari, D. et. al., WorldSID prototype dummy biomechanical response, Stapp Car Crash Journal, Vol. 45, 2001

5. Robbins, D. H., Anthropometric specifications for the mid-sized male dummy, Final report, contract DTNH22-80-C-07502, U.S. Department of Transportation National Highway Traffic Safety Administration, December 1983

6. Hodgson, V.R. and Thomas, L.M. (1975) Head impact response. Vehicle Research Institute Report – VRI 7.2. Society of Automotive Engineers.

7. Ewing, C.L. et al. (1977) Measurement of head, T1, and pelvic response to Gx impact acceleration. SAE 770927, Proc. 21st Stapp Car Crash Conference, pp. 507-545. Society of Automotive Engineers, Warrendale, PA

8. Wismans et al. (1986) Omni-directional head-neck response, SAE 861893. Proc. Of the 30th Stapp Car Conference, Society of Automotive Engineers, Warrendale, P.A

9. Patrick, L.M. and Chou, C.C. (1976) Response of the human neck flexion, extension and lateral flexion. Final report VRI-7.3. Society of Automotive Engineers, Warrendale, PA

10. Tarriere, C. et al. (1979) Synthesis of human tolerances obtained from lateral impact simulations. Proc. 7th International Technical Conference on Experimental Safety Vehicles, pp. 359-374. National Highway Traffic Safety Administration U.S. Department of Transportation, Washington DC

11. Bendjellal, F. et al. (1984) APR biomechanical data. Nanterre, France

12. Irwin, A.L. (1994) Analysis and CAL3D model of the shoulder and thorax responses of seven cadavers subjected to lateral impacts. Ph.D. Thesis. Wayne State University, Detroit, MI.

13. Eppinger, R.H. et al. (1978) Development of a promising universal thoracic trauma prediction methodology. SAE 780891. Proc. 22nd Stapp Car Crash Conference, pp. 209-268. Society of Automotive Engineers, Warrendale, PA.

14. Viano, D.C. (1989) Biomechanical responses and injuries in blunt lateral impact. SAE 892432. Proc. 33rd Stapp Car Crash Conference, pp. 227-257. Society of Automotive Engineers, Warrendale, PA.

15. Stalnaker, R.L. et al. (1979) Modification of Part 572 dummy for lateral impact according to biomechanical data. SAE 791031. Proc. 23rd Stapp Car Crash Conference. Society of Automotive Engineers, Warrendale, PA.

16. Marcus, J.H. et al. (1983) Human response and injury from lateral impact. SAE 831634. Proc. 27th Stapp Car Crash Conference, pp. 419-433. Society of Automotive Engineers, Warrendale, PA.

17. Cavanaugh et al., (1990) Biomechanical response and injury tolerance of the thorax in twelve sled side impacts. SAE 902307, Proc. 34th Stapp Car Conference. Society of Automotive Engineers, Warrendale, PA.

18. Cavanaugh et al., (1990) Biomechanical response and injury tolerance of the pelvis in twelve sled side impacts. SAE 902307, Proc. 34th Stapp Car Conference. Society of Automotive Engineers, Warrendale, PA.

19. Cesari, D. et al. (1980) Evaluation of pelvic fracture tolerance in side impact. SAE 801306. Proc. 24th Stapp Car Crash Conference. Society of Automotive Engineers, Warrendale, PA.

20. Cesari, D. and Ramet (1982) Pelvic tolerance and protection criteria in side impact. SAE 821159. Proc. 26th Stapp Car Crash Conference. Society of Automotive Engineers, Warrendale, PA.

21. Cesari, D. et al. (1982) Tolerance of human pelvis to fracture and proposed pelvic protection criterion to be measured on side impact dummies, Proc. 9th International Technical Conference on Experimental Safety Vehicles, pp 261-268, National Highway Traffic Safety Administration U.S.Department of Transportation, Washington DC

22. Irwin, A.L. et al. (1989) EUROSID and SID impact responses to the response corridors of the International Standards Organisation, SAE paper No. 890604, Society of Automotive Engineers, Warrendale, PA.

23. Byrnes, K. et al. (2002) ES-2 dummy biomechanical responses, Proc. 46th Stapp Car Crash Conference, No. 2002-22-0018, Society of Automotive Engineers, Warrendale, PA.

24. Beebe, M.S. (1990) What is BioSID? SAE paper No. 900377, Society of Automotive Engineers, Warrendale, PA.

25. Rhule, H. et al. (2002) Development of a new biofidelity ranking system for anthropomorphic test devices. Stapp Car Crash Journal 46 (November 2002)

APPENDIX A: HEAD TESTS

TABLE A1. Head Test 1 - Lateral Head Drop Results

Head Test 1	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Left Impact	Peak Resultant Acceleration (non-impact side of head)	g	100	150	177	177	177

APPENDIX B: NECK TES TS

TABLE B1. Neck Test 1 – 7.2 G Sled Test

Neck	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 1	Peak T1 Horizontal Accel, Ay	g	12	18	15	15	13
	Peak T1 Horizontal Disp wrt sled, Dy	mm	46	63	58	53	51
	Peak Head C.G. Horiz. Displ wrt T1, Dy	mm	130	162	131	115	116
	Peak Head C.G. Vert. Displ wrt T1, Dz	mm	64	94	37	42	41
	Time of Peak Head Excursion, Dy(s)	s	0.159	0.175	0.183	0.175	0.177
	Peak Head Lateral Accel, Ay	g	8	11	11	-	-
	Peak Head Vert. (downward) Accel, -Az	g	8	10	12	-	-
	Peak Head Flexion, θx	degrees	44	59	60	56	58
	Peak Neck Twist, θz	degrees	-45	-32	-17*	-15*	-18*

* Data generated from rotational accelerometers

TABLE B2. Neck Test 2 – 6.7 G Sled Test

Neck	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 2	Peak Flexion Angle, θx	degrees	40	50	51*	49*	55*
	Peak Moment about A-P Axis at O.C., Mx	N·m	40	50	30	27	29
	Peak Moment about R-L Axis at O.C., My	N·m	20	30	13	12	11
	Peak Twist Moment, Mz	N·m	15	20	9	9	10
	Peak Shear Force at O.C., Fy	N	750	850	451	416	473
	Peak Tension Force at O.C., Fz	N	350	400	561	519	573
	Peak P-A Shear Force, Fx	N	325	375	158	144	159
	Peak Resultant Head Accel	g	18	24	16*	15*	17*

TABLE B3. Neck Test 3 – 12.2 G Sled Test

Neck	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 3	Peak Lateral Accel of T1, Ay	g	17	23	26	26	23
	Peak Head C.G. Lateral Accel, Ay	g	25	47	n/a	n/a	n/a
	Peak Head C.G. Horiz. Displ. wrt Sled, Dy	mm	185	226	202	205	206
	Peak Head Flexion, θx	degrees	62	75	74	79	80
	Peak Head Torsion, θz	degrees	62	75	20*	21*	22*

n/a = lost data

APPENDIX C: SHOULDER TESTS

TABLE C1. Shoulder Test 1 Results

Shoulder	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 1 (Left)	Peak Shoulder Deflection	mm	34	41	34	35	35
Test 1 (Right)	Peak Shoulder Deflection	mm	34	41	28	28	29

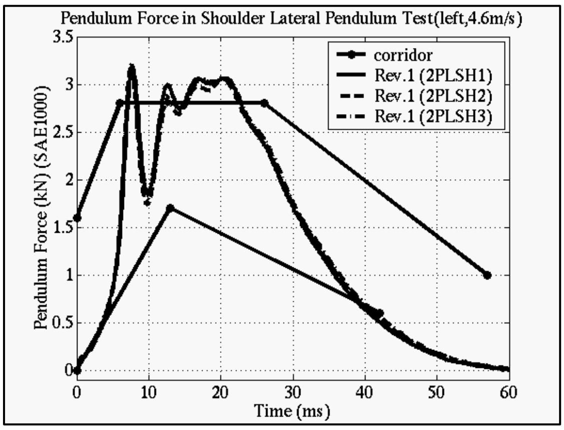

Figure Cl. Shoulder Test 1 Pendulum Force Left

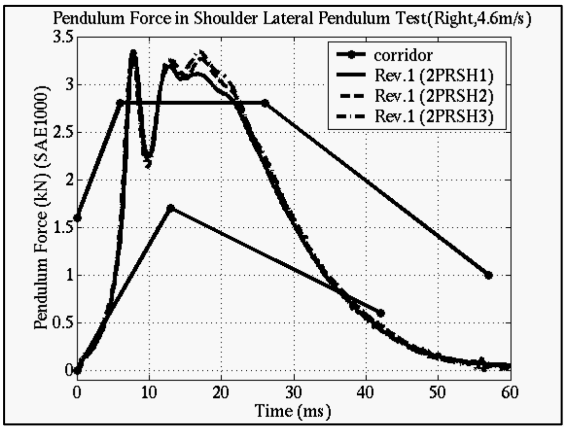

Figure C2. Shoulder Test 1 Pendulum Force Right

TABLE C2. Shoulder Test 2 – 7.2 G Sled Test

Shoulder	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 2	Peak T1 Horizontal Accel, Ay	g	12	18	15	15	13
	Peak Horizontal Displ. T1	mm	46	63	58	53	51

TABLE C3. Shoulder Test 3 – 12.2 G Sled Test

Shoulder	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 3	Peak Lateral Accel of T1, Ay	g	17	23	26	26	23

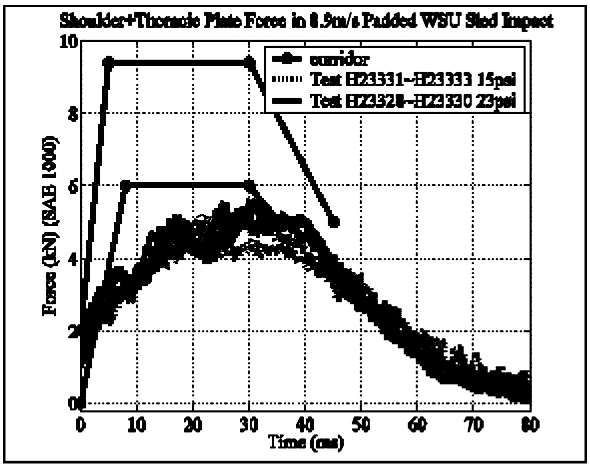

Figure C3. Shoulder Test 4 Shoulder+Thoracic Plate Force

APPENDIX D: THORAX TESTS

TABLE D1. Thorax Test 3 and 5 results

Thorax	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 3 (Left)	Thoracic Rib Deflection	mm	26	38	38	36	40
Test 3 (Right)	Thoracic Rib Deflection	mm	26	38	25	37	29
Test 5	T1 Acceleration	g	82	122	45	41	46
	T12 Acceleration	g	71	107	42	44	35
	Thoracic Rib Acceleration	g	64	100	96	83	67

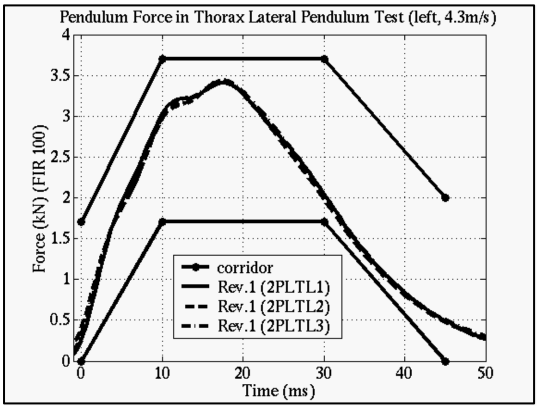

Figure D1. Thorax Test 1 Pendulum Force Left

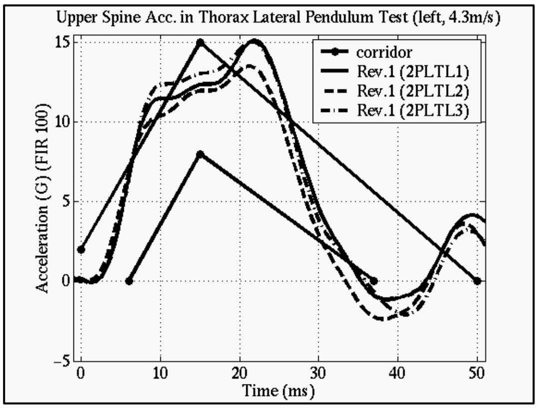

Figure D2. Thorax Test 1 Upper Spine Acceleration

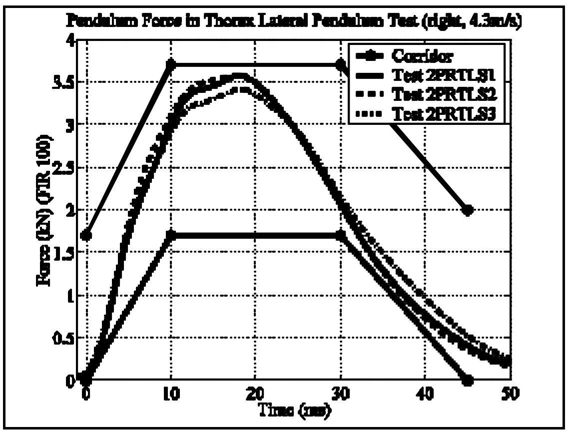

Figure D3. Thorax Test 1 Pendulum Force Right

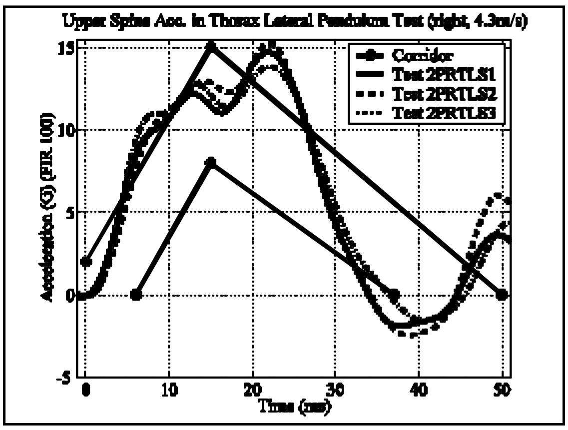

Figure D4. Thorax Test 1 Upper Spine Acceleration

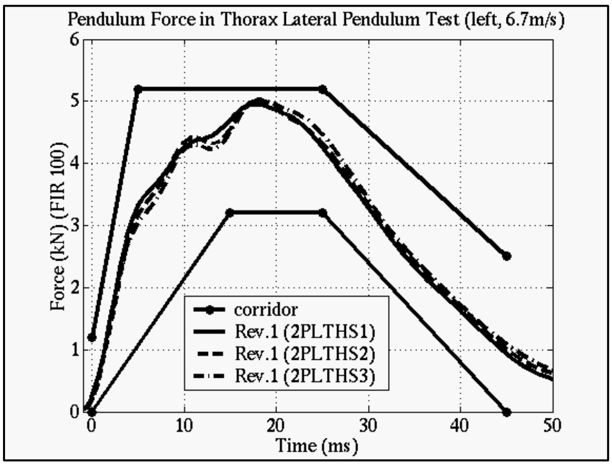

Figure D5. Thorax Test 2 Pendulum Force Left

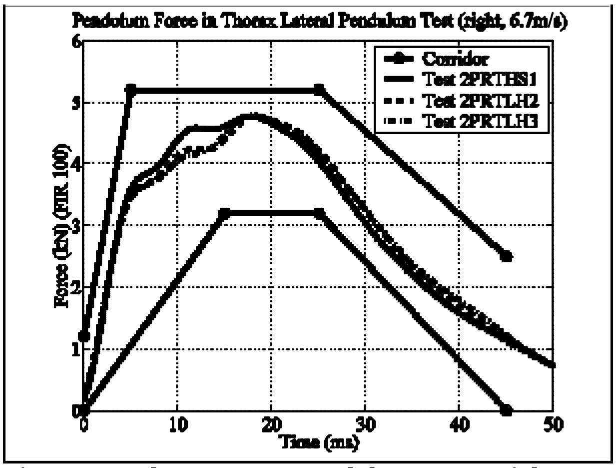

Figure D6. Thorax Test 2 Pendulum Force Right

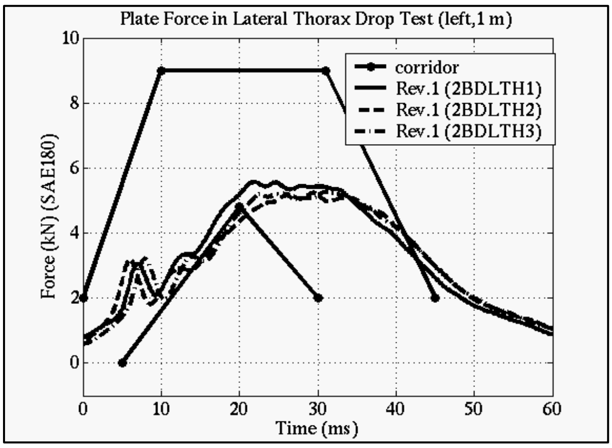

Figure D7. Thorax Test 3 Plate Force Left

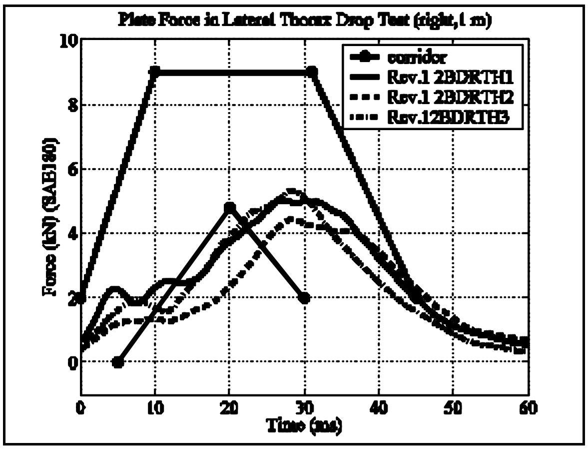

Figure D8. Thorax Test 3 Plate Force Right

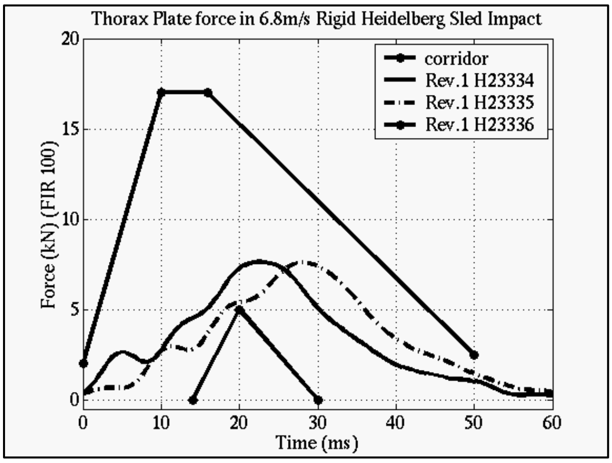

Figure D9. Thorax Test 5 Plate Force Left

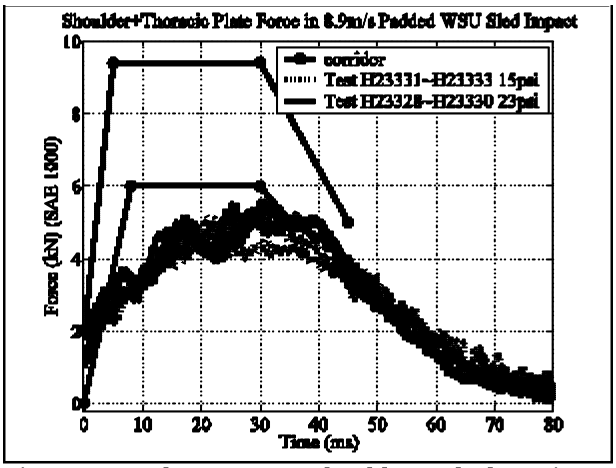

Figure D10. Thorax Test 6 Shoulder and Thoracic Plate Force

APPENDIX E: ABDOMEN TESTS

TABLE E1
Abdomen Test 1 and 2 results

Abdomen	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 1 (Left)	T12 Acceleration	g	29	35	32	35	34
	Abdominal Rib Acceleration	g	100	125	149	144	140
	Abdominal Rib Displacement	mm	>41		54	56	59
Test 1 (Right)	T12 Acceleration	g	29	35	34	32	31
	Abdominal Rib Acceleration	g	100	125	158	156	177
	Abdominal Rib Displacement	mm	>41		52	54	56

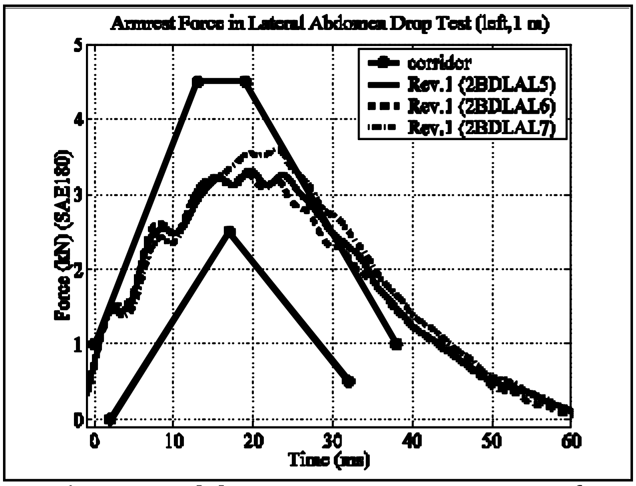

Figure E1. Abdomen Test 1 Armrest Force Left

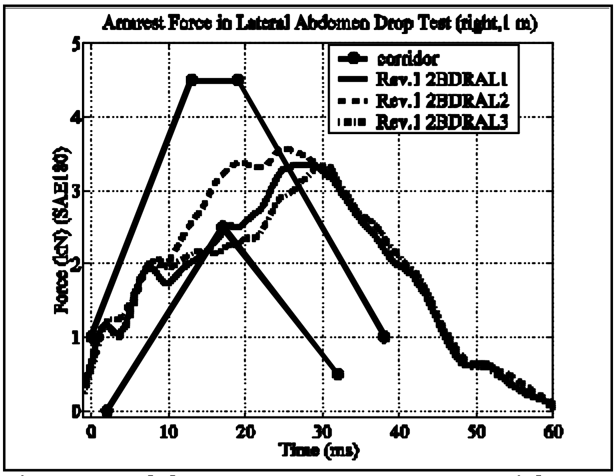

Figure E2. Abdomen Test 1 Armrest Force Right

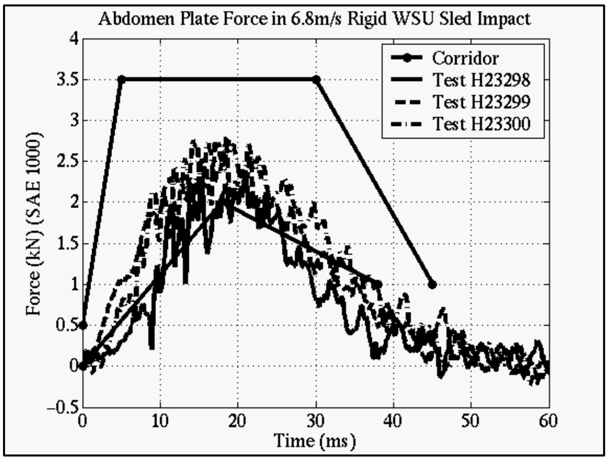

Figure E3. Abdomen Test 3 Abdomen Plate Force

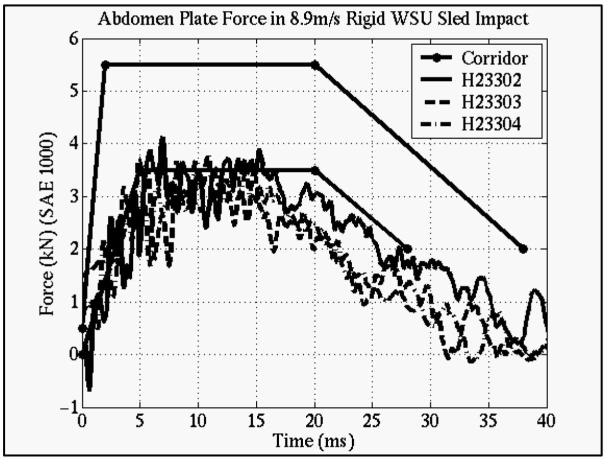

Figure E4. Abdomen Test 4 Abdomen Plate Force

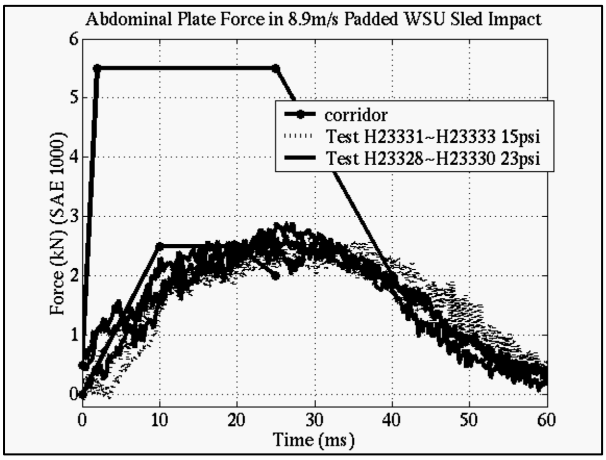

Figure E5. Abdomen Test 5 Abdomen Plate Force

APPENDIX F: PELVIS TESTS

TABLE F1. Pelvis Test 3, 4, 7, 8, 10, 11, 12 and 13 results

Pelvis	Parameters	Units	Lower Bound	Upper Bound	Run 1	Run 2	Run 3
Test 3 (Left)	Peak Pelvis Acceleration	g	37	45	32	34	36
Test 3 (Right)	Peak Pelvis Acceleration	g	37	45	30	31	33
Test 4 (Left)	Peak Pelvis Acceleration	g	63	77	55	58	51
Test 4 (Right)	Peak Pelvis Acceleration	g	63	77	44	48	49
Test 7	Pelvis Acceleration	g	63	77	57	60	60
	Pelvis Force	kN	6.4	7.8	7.7	7.7	7.0
Test 8	Pelvis Acceleration	g	96	116	103	-	-
	Pelvis Force	kN	22.4	26.4	N/a***	-	-
Test 10	Pelvis Acceleration	g	85	115	71	63	56
Test 11	Pelvis Acceleration	g	111	151	103	105	103
Test 12	Pelvis Acceleration	g	37	51	33	30	33
Test 13	Pelvis Acceleration	g	65	89	37	32	-

***– data exceeded full scale setting

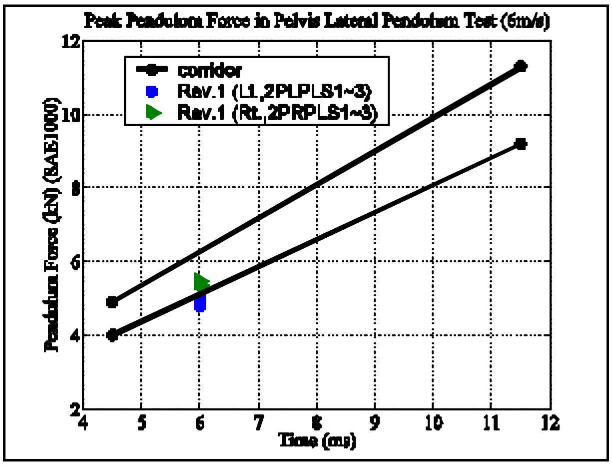

Figure F1. Pelvis Test 1 Pendulum Force

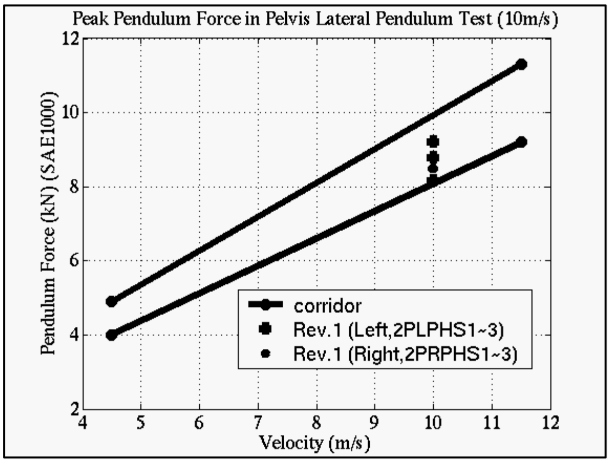

Figure F2. Pelvis Test 2 Pendulum Force

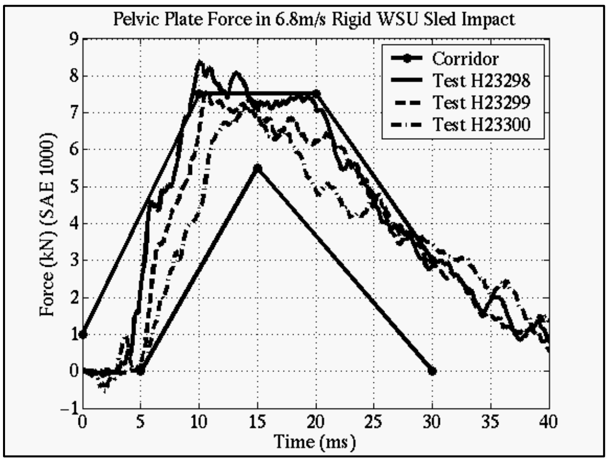

Figure F3. Pelvis Test 10 Pelvic Plate Force

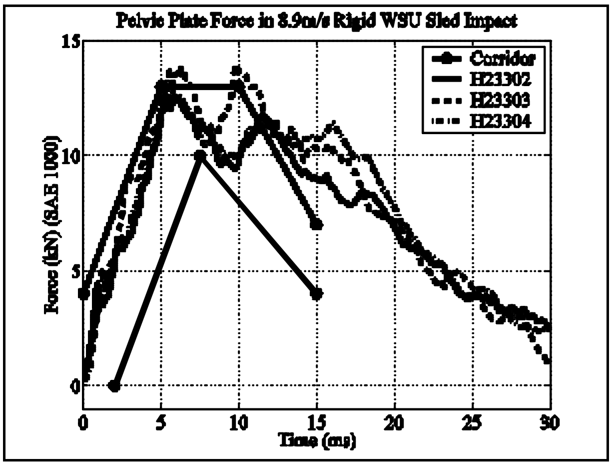

Figure F4. Pelvis Test 11 Pelvic Plate Force

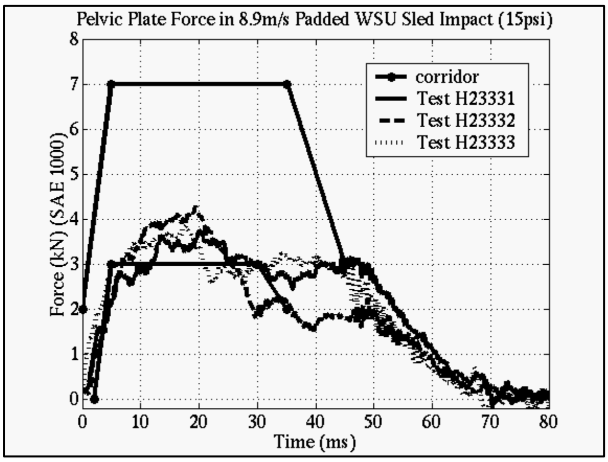

Figure F5. Pelvis Test 12 (15psi) Pelvic Plate Force

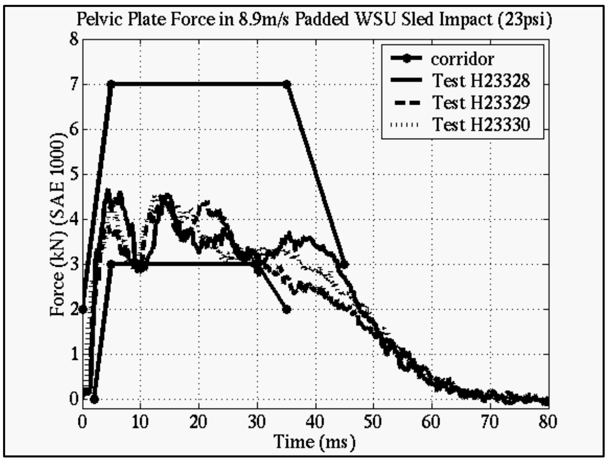

Figure F6. Pelvis Test 13 (23psi) Pelvic Plate Force

APPENDIX G: BIOFIDELITY COMPARISION OF MID MALE SIDE IMPACT DUMMIES

		SID	BioSID	ES-2	WorldSID Prototype Rev. 1
Requirement	**Test Description**	**Test Biofidelity**	**Test Biofidelity**	**Test Biofidelity**	**Test Biofidelity**
Head Test 1	200 mm Rigid Drop	0	10	5	10
Head Test 2	1200 mm Rigid Drop	0	0	*	N. M.
Head Biofidelity		**0**	**6.7**	**5**	**10**
Neck Test 1	7.2 G Sled Impact	1.5	7	5.9	7.0
Neck Test 2	6.7 G Sled Impact	*	*	1.9	2.4
Neck Test 3	12.2 G Sled Impact	1.7	6	5.9	6.7
Neck Biofidelity		**1.6**	**6.7**	**4.4**	**5.2**
Shoulder Test 1	4.5 m/s Pendulum	2.9	5.7	2.9	6.1
Shoulder Test 2	7.2 G Sled Impact	0	7.5	2.5	10
Shoulder Test 3	12.2 G Sled Impact	0	10	10	6.7
Shoulder Test 4	8.9 m/s Padded WSU Sled	*	*	7.5	5
Shoulder Biofidelity		**1.2**	**7.3**	**5.3**	**6.7**
Thorax Test 1	4.3 m/s Pendulum	5	7.2	5	**7.8**
Thorax Test 2	6.7 m/s Pendulum	*	5	5	10
Thorax Test 3	1.0 m Rigid Drop	5	7.5	6.7	7.9
Thorax Test 4	2.0 m Padded Drop	5	7.7	*	N. M.
Thorax Test 5	6.8 m/s Rigid Heidelberg Sled	5	5	5.2	7.1
Thorax Test 6	8.9 m/s Padded WSU Sled	*	*	4.8	5
Thorax Biofidelity		**5**	**6.3**	**5.2**	**7.7**
Abdomen Test 1	1.0 m Rigid Drop	1.6	4.3	0	5.7
Abdomen Test 2	2.0 m Rigid Drop	3.5	3.2	1.1	6.8
Abdomen Test 3	6.8 m/s Rigid WSU Sled	*	*	5	8.3
Abdomen Test 4	8.9 m/s Rigid WSU Sled	*	*	1.3	5
Abdomen Test 5	8.9 m/s Padded WSU Sled	*	*	10	5
Abdomen Biofidelity		**2.5**	**3.8**	**2.6**	**6.0**
Pelvis Test 1	6.0 m/s Pendulum Impact	0	10	5.0	7.5
Pelvis Test 2	10 m/s Pendulum Impact	*	*	*	10
Pelvis Test 3	0.5 m Rigid Drop	2.5	5	8.3	5
Pelvis Test 4	1.0 m Rigid Drop	5	0	10	3.3
Pelvis Test 5	2.0 m Padded Drop	7.5	5	*	N. M.
Pelvis Test 6	3.0 m Padded Drop	*	*	*	N. M.
Pelvis Test 7	6.8 m/s Rigid Heidelberg Sled	0	2.2	0	7.8
Pelvis Test 8	8.9 m/s Rigid Heidelberg Sled	0	5	4.7	10
Pelvis Test 9	8.9 m/s Padded Heidelberg Sled	5	0	*	N. M.
Pelvis Test 10	6.8 m/s Rigid WSU Sled	*	*	4.0	6.9
Pelvis Test 11	8.9 m/s Rigid WSU Sled	*	*	1.6	5.9
Pelvis Test 12	8.9 m/s 15 psi Padded WSU Sled	*	*	10	5
Pelvis Test 13	8.9 m/s 23 psi Padded WSU Sled	*	*	7.8	5.6
Pelvis Biofidelity		**2.2**	**4**	**5.3**	**7.3**
Dummy Overall Biofidelity		**2.3**	**5.7**	**4.6**	**7.2**

* TEST NOT CONDUCTED